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Airborne Downlooking Lidar Measurements during State 78

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16. ABSTRACT

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The lidar estimates of mixing layer height were usually slightly higher than *in situ* counterparts, presumably because aerosols may rise and become trapped above the base of the elevated stable layer. Values of plume rise computed using the Briggs models were generally similar to those indicated from lidar measurements although considerable scattering of data existed; supplementary data indicated that the scatter could be reduced with the inclusion of the vertical shear of the horizontal wind in the models. When adjustment with respect to sampling time was accomplished, the lidar values of plume dimensions compared reasonably well with values obtained using data collected by *in situ* measurement platforms. The situations sampled by the lidar were almost exclusively at night or in the daytime when the plume was above the top of the mixing layer. For such situations, effects of initial mixing due to buoyancy and diffusion are apparent in the vertical plume spread. Effects of initial mixing due to buoyancy, turning of the horizontal wind with height, and diffusion are apparent in the crosswind plume spread; this was surmised through comparison of the lidar plume dimensions with the Pasquill–Gifford dispersion curves. The data, thus, provide additional evidence that information on the plume buoyancy, turning of the wind with height, and the height of the plume in relation to that of the mixing layer must be included in any new scheme or any adaptation of an existing scheme for the estimation of the spread for large, elevated buoyant plumes.

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AIRBORNE DOWNLOOKING LIDAR MEASUREMENTS DURING STATE 78*

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Abstract—EPA's airborne downlooking dye lidar was operated during the STATE field program in western Kentucky/Tennessee in the summer of 1978. In this paper, lidar estimates of height of the atmospheric mixing layer are shown and compared with *in situ* measurements. Lidar estimates of crosswind and vertical dimensions of TVA power plant plumes are compared with appropriate literature values and with *in situ* estimates from data compiled by other STATE investigators; wherever necessary, data are adjusted to ensure compatibility with respect to sampling time. In addition, lidar measurements of plume rise are compared with model calculations.

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INTRODUCTION

Concern over the rising ambient sulfate concentrations in the northeastern United States prompted the U.S. Environmental Protection Agency (EPA) to establish the Sulfur Transport and Transformation in the Environment (STATE) program. The program has as its goal the quantification of the impact of emitted pollutants and transformation products from distant discrete sources and source complexes on local air quality. The first major STATE field experiment was the August 1978 Tennessee Plume Study (TPS) conducted in the area surrounding the Cumberland Steam Plant in northwestern Tennessee (Fig. 1). The Cumberland Steam Plant is a coal-fired, base-load electrical generating station with a capacity of 2600 MW from two 1300 MW boilers, each connected to its own 305-m stack. Investigators from governmental agencies, universities, research institutes, and private contractors participated in the TPS in an attempt to define plume transport, diffusion, transformation, and removal rates out to distances of several hundred kilometers from the plant. Further details on the TPS and on the overall STATE program are found in Schiermeier *et al.* (1979).

The EPA airborne downlooking dye lidar was one of the measurement systems used in this study. Its participation had several objectives:

(1) To determine the transport and diffusion of the effluent from the power plant, especially plume dimensions.
(2) To map the spatial and temporal variations in the height of the atmospheric mixing layer over the study area.
(3) To locate and delineate the power plant plume for the other measurement platforms.
(4) To expand the temporal and spatial extent and extend the detail of experiments.

This paper is primarily concerned with the evaluation of data collected by the lidar system in terms of the first two objectives.

AIRBORNE DOWNLOOKING DYE LIDAR SYSTEM

The airborne downlooking lidar system operated by EPA during the STATE TPS study was developed by the Environmental Monitoring Systems Laboratory in Las Vegas, Nevada (EMSL-LV). The system uses a flashlamp-pumped dye laser with a Fresnel lens telescope receiver. A flowchart of the system is shown in Fig. 2. The returned laser signal is preprocessed to

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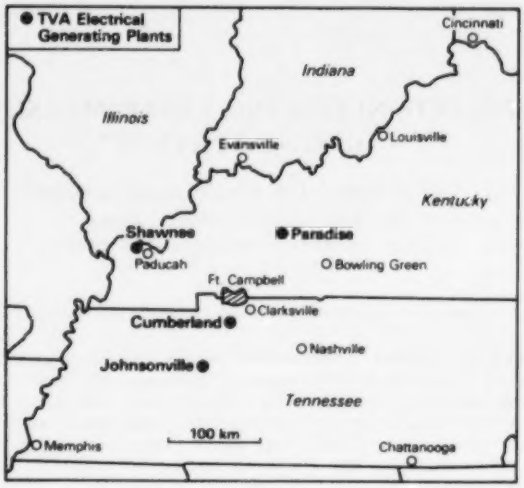


Fig. 1. Map showing area of Tennessee Plume study.

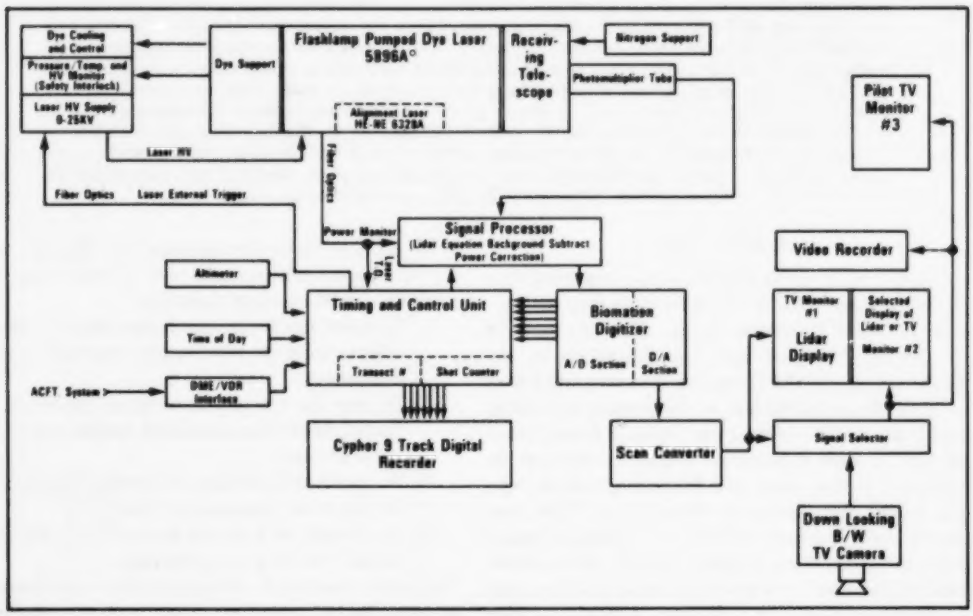


Fig. 2. Flow chart of Airborne Dye Lidar system.

normalize for instantaneous power variations and correct for the geometrical range dependence (lidar equation). Data are permanently recorded via digitization of aerosol backscatter signature on a digital tape recorder. An on-board television monitor provides realtime display for operator use. This realtime display is recorded by a video tape recorder used for playback, for preliminary analyses immediately following flights, and for backup data in case of failure of the digital system. The maximum firing rate is 1 Hz which, when combined with the aircraft ground speed, determines the minimum horizontal resolution of about 50 m. The theoretical vertical resolution of 45 m is determined by the laser pulse width of 250 ns. These specifications are included in the system and operational parameters which are presented in Table 1.

Table 1. System and operational parameters for the Airborne Dye Lidar System

System parameters:
Weight: 375 kg (including power inverters, navigational system, TV system and monitor oscilloscope)

Volume: 0.9 m^3
Electronics data processor rack—0.3 m^3
Laser support rack—0.2 m^3
Lidar assembly—0.2 m^3
Telescope—0.2 m^3
Power consumption: 28 VDC-50A (1400 W)
Frequency: 0.5896 μm
Firing rate: 1 pulse per 1, 2, 4, or 6s
Output format: 6 bit resolution
Digitization interval: 100 ns
Navigational support: Dedicated system with 2 DME and 1 VOR units

Operational parameters:
Aircraft type: Small twin engine cargo
Minimum operational altitude: 1500 m AGL
Smallest horizontal resolution element: 50 m
Vertical resolution element: 45 m
Ground footprint: 20 m
Beam divergence: 10 mrad
Power output: 175 MJ maximum

ANALYSIS OF LIDAR AND SUPPLEMENTARY DATA

Plume dimensions

Values of total plume width and thickness were computed for lidar cross sections of the Cumberland power plant plume. For those occasions when the lidar transects were at an oblique angle to the plume, values of the widths were adjusted using pilot balloon wind data collected over the study area by the Tennessee Valley Authority (TVA), (Crawford *et al.*, 1979) to obtain values for cross sections normal to the plume. Values of the resultant widths and the thicknesses were then converted to values of equivalent Gaussian crosswind (σ_y) and vertical (σ_z) standard deviations, respectively, through the relations

$$\sigma_y = \text{width}/4.3 \text{ and} \quad (1)$$

$$\sigma_z = \text{thickness}/4.3. \quad (2)$$

These values, particularly those of σ_y, can be considered to be quasi-instantaneous values since the lidar aircraft platform traversed the plumes in a few seconds to a few minutes, typically in a few tens of seconds. To allow for comparison with specific literature data, values of σ_y were also converted to values appropriate for a 3-min sampling time through the relation (Hanna *et al.*, 1977)

$$\sigma_{y3\text{min}} = \sigma_y \left[\frac{t_{\sigma_y}}{3\,\text{min}} \right]^{-1/5} \quad (3)$$

where t_{σ_y} is the sampling time (in minutes) appropriate for the lidar plume transect. Occasionally, the airborne lidar made multiple traverses of the plume at the same distance downwind. Data for such multiple traverses were superimposed using a fixed coordinate system, and single values of σ_y and σ_z were determined for each of the composite cross sections as previously described.

On a few occasions, other measurement platforms made *in situ* transects of the Cumberland power plant plume in proximity in time and space to those of the airborne lidar. The available data from these platforms were used to compute plume dimensions in the same manner as for the lidar data.

Figures 3(a) and 3(b), respectively, present values of lidar σ_y and lidar $\sigma_{y3\,\text{min}}$ versus comparable values for light-scattering coefficient/sulfur dioxide measurements made using aircraft from Environmental Measurements, Inc. (EMI) and the Brookhaven National Laboratory (BNL); the *in situ* data were insufficient to permit calculations of σ_z. Both aircraft used fast response Meloy 5A-285 instruments for sulfur dioxide measurements and MRI nephelometers for light-scattering coefficient measurements (Model 1561 for EMI and Model 1550 for BNL). The data plus details on the measurements, instruments, quality assurance and data processing for the BNL and EMI aircraft during the TPS are presented by Gillani *et al.*, (1979a) and (1979b).

As shown in Figs 3(a) and 3(b), reasonably good relationships appear to exist between crosswind plume dimensions for the lidar and *in situ* platforms. The unadjusted lidar values are generally smaller than their *in situ* counterparts (Fig. 3a). The lidar $\sigma_{y3\,\text{min}}$ are closer in value to the *in situ* $\sigma_{y3\,\text{min}}$ although remaining slightly lower, especially for the higher values (Fig. 3b). The former finding for the time adjusted data is encouraging but not altogether unexpected since the lidar aircraft usually traversed the plumes faster than the other aircraft. One can only speculate on the latter finding, especially with such a small sample size. The *in situ* values may be slightly inflated since the BNL and EMI data were reported as 5s averages. Also, the lidar with a pulse width of 45 m may not have been able to fully identify plume edges for the thin, stable plumes that were generally sampled, especially for longer distances from the source when the crosswind spread became very large (see Fig. 4).

Plots of lidar σ_y, $\sigma_{y3\text{min}}$, and σ_z vs distance downwind of the Cumberland plant are presented in Figs 4(a), 4(b), and 4(c), respectively. Data were obtained out to 175 km from the source under certain conditions. The Pasquill–Gifford (P–G) curves, appropriate for a 3-min sampling time, are superimposed on these figures as a frame of reference (Turner, 1970). Note that the P–G curves are based on measured data to only about 800 m from the source and are strictly applicable to non-buoyant, ground-level emissions. As is shown, the vertical dispersion is appropriate for neutral (D) to stable conditions (E/F), and the plume thickness increases very slowly with distance downwind (Fig. 4c). This is not too surprising since many of the transects occurred at night and nearly all of the other transects took place when the plume was above the top of the mixing layer. The high values of σ_z near the source likely result from spreading due to initial

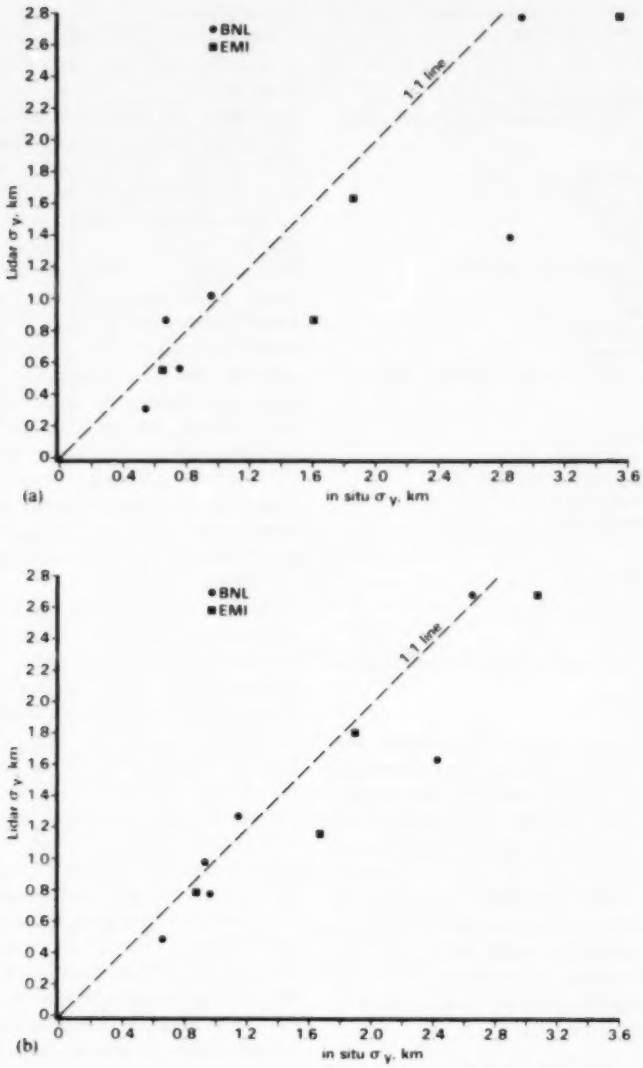
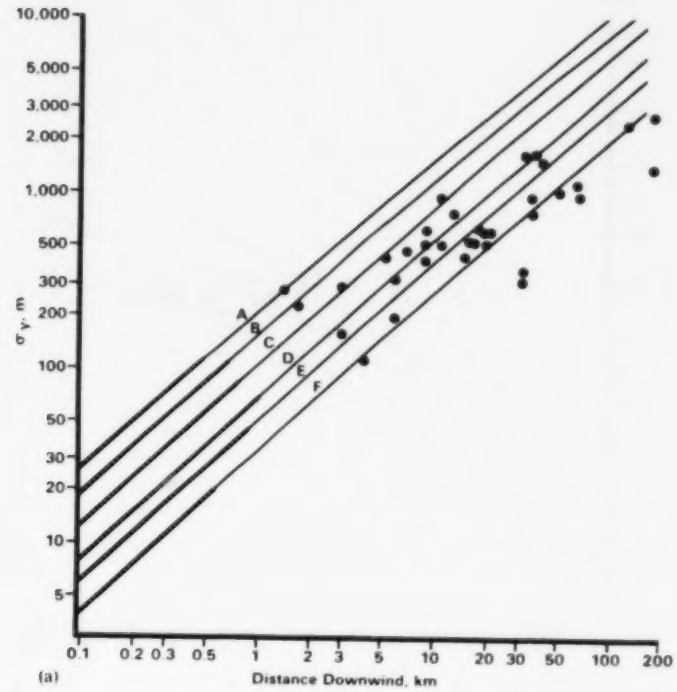
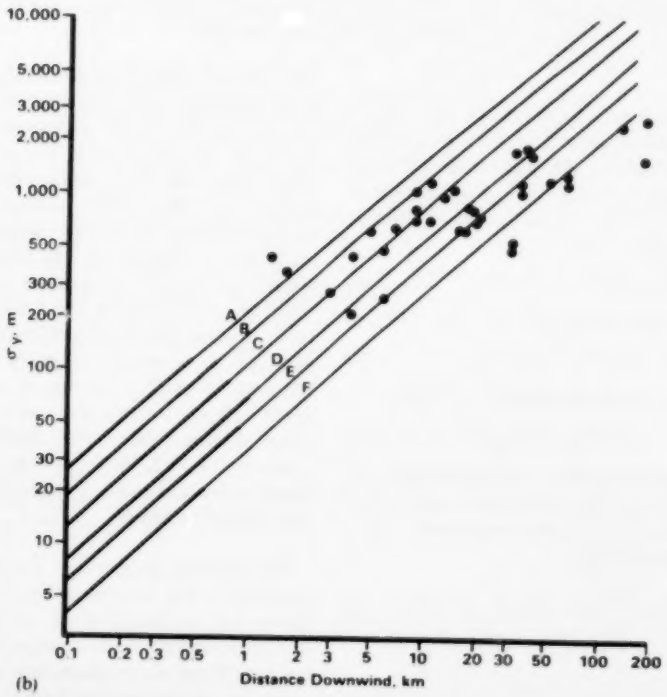


Fig. 3.(a) Crosswind plume dispersion coefficient from Airborne Lidar measurements as a function of crosswind plume dispersion coefficient from *in situ* platform measurements for Cumberland power plant. (b). Same as 3(a) except for crosswind plume dispersion coefficients adjusted for 3-min sampling time.

plume buoyancy. Comparable values for σ_y (Fig. 4a) varied between slightly unstable (C) and stable (E/F). The values for $\sigma_{y\,3\,min}$ (Fig. 4b) were generally about one stability class higher (more unstable) than those for σ_y for the overall range of downwind distances covered. Horizontal crosswind spreading for the Cumberland plume also appears to increase more slowly with downwind distance than for the P–G curves. Thus, it is likely that the values for σ_y and $\sigma_{y\,3\,min}$ include the effect of directional shear of the horizontal wind with altitude in addition to effects of turbulent diffusion and initial plume buoyancy.

Values of plume dimensions for the composite cross sections are not shown here. Only a few occasions appropriate for the compositing of data existed, and on only two of the latter occasions were more than two cross sections available. Values of σ_z for the composite cross sections were generally similar to those for the individual cross sections. Values of σ_y for the composites were generally somewhat larger than for the individual cross sections. However, it was not possible to speculate on the relationship between plume dimensions for time-averaged and quasi-instantaneous plumes for such a small sample.


10,000
5,000
3,000
2,000
1,000
500
300
200
100
50
30
20
10
5
σy, m
A
B
C
D
E
F
0.1 0.2 0.3 0.5 1 2 3 5 10 20 30 50 100 200
(a)
Distance Downwind, km


10,000
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5
σy, m
A
B
C
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(b)
Distance Downwind, km

Fig. 4. (a) and (b).

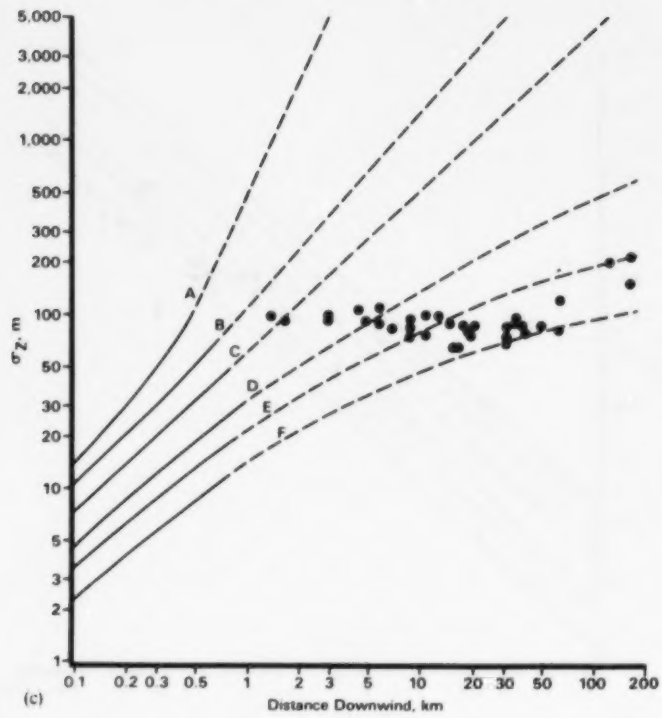

Fig. 4.(a) Crosswind plume dispersion coefficient from Airborne Lidar measurements as a function of distance downwind from Cumberland power plant. Pasquill–Gifford dispersion curves A–F are superimposed. (b). Same as 4(a) except for crosswind plume dispersion coefficient adjusted for 3-min sampling time. (c). Same as 4(a) except for vertical plume dispersion coefficient.

Plume rise

Comparisons were made of plume centerline height estimated from lidar measurements and using plume rise equations. Plume rise, Δh, was computed using equations developed by Briggs (1969). For transitional rise in stable ($x \leqslant 2.4\,uS^{-1/2}$) and neutral or unstable ($x < 10h_s$) situations

$$\Delta h = 1.6\,F^{1/3}u^{-1}x^{2/3}. \tag{4}$$

For final rise in stable situations ($x > 2.4\,uS^{-1/2}$)

$$\Delta h = 2.9\,F^{1/3}u^{-1/3}S^{-1/3}, \tag{5}$$

and in neutral or unstable situations ($x \geqslant 10h_s$)

$$\Delta h = 1.6\,F^{1/3}u^{-1}(10h_s)^{2/3} \tag{6}$$

where x is distance downwind, h_s is stack height, u is wind speed at stack top, S is a stability parameter and F is stack heat efflux. F and S were, respectively, calculated using the relationships

$$F = \frac{g}{T_0}(T_0 - T)\,w\,r^2 \tag{7}$$

and

$$S = \frac{g}{\bar{T}}\frac{\partial\theta}{\partial Z}, \tag{8}$$

where g is acceleration of gravity, T_0 is absolute stack gas temperature, T is absolute ambient air temperature at stack top, w is vertical velocity of stack effluent, r is radius of the stack at its top, θ is potential air temperature, and $\bar{T}$ is average absolute ambient air temperature. The stability parameter was computed for the layer between the top of the stack and the top of the plume as indicated by lidar using data for rawinsonde and aircraft temperature soundings for the study area compiled by the TVA (Reisinger *et al.*, 1979). Wind speeds at stack top were estimated from pilot balloon soundings taken by the TVA near the Cumberland plant (Crawford *et al.*, 1979), and the power generation data and stack parameters were obtained from Pooler (1980) from information furnished by the TVA. Finally, values of plume centerline height were taken as $h + \Delta h$ were h is the Cumberland stack height of 305 m.

The resulting comparisons for final plume rise are presented in Fig. 5. A reasonably good relationship is shown for the small range of situations sampled (mostly stable) although considerable scatter exists in the data. Some of this scatter can be attributed to the crudeness of the meteorological data used for the plume rise calculations. A detailed inspection of the

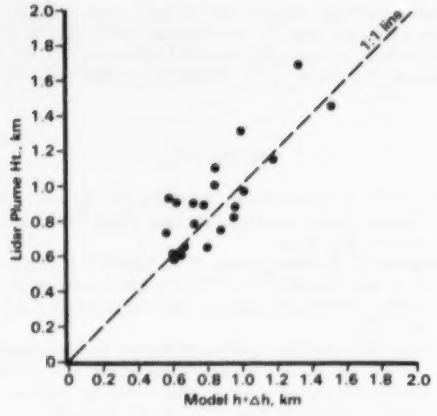

Fig. 5. Plume centerline height from Airborne Lidar measurements as a function of plume centerline height calculated from Briggs plume rise models for Cumberland power plant.

pilot balloon wind data, however, indicated that the scatter could probably be reduced if the shear of the wind with height above the top of the stacks had been considered in the plume rise equations. At 305 m above ground, the Cumberland stacks are sometimes below and sometimes above the level of the peak wind for stable situations. The relationship for transitional rise (not shown) is similar to that shown in Fig. 5 although only four cases of such rise were monitored by the lidar, making the data sample very small.

Mixing layer height

Comparisons were made of the height of the atmospheric mixing layer as determined for the lidar data and from rawinsonde and aircraft temperature soundings over the study area as reported by Ching (1979). For the lidar data, this height was taken as the apparent extent of surface-based mixing as indicated by aerosol backscatter while for the *in situ* data it was the height of the base of the lowest elevated stable layer. The resulting comparisons shown in Fig. 6 indicate that a good relationship exists between the two quantities although the lidar-derived values are generally slightly larger than the *in situ* values. A plausible explanation for the latter result is that aerosol particles, which are sensed by the lidar, rise above the base of an elevated stable layer where they are trapped. Many of the larger differences between the lidar and *in situ* values were for late morning periods during the rapid growth of the mixing layer and hence vigorous interfacial mixing through the elevated stable layer. Also, as discussed by Coulter (1979), larger lidar-

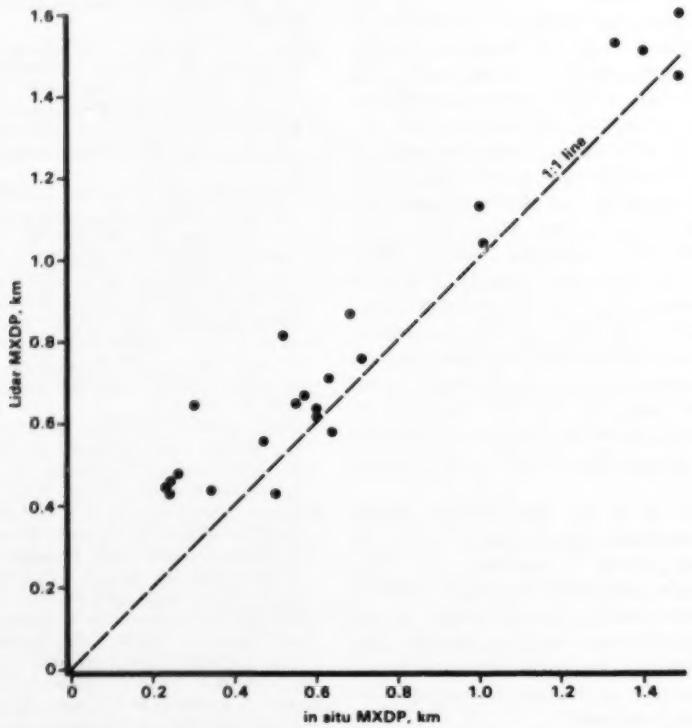

Fig. 6. Height of atmospheric mixing layer (MXDP) from Airborne Lidar measurements as a function of height of atmospheric mixing layer from rawinsonde or aircraft temperature soundings.

derived values may be indicated as the elevated stable layer dissipates or rises owing to the incorporation of aerosols trapped aloft earlier.

DISCUSSION AND CONCLUDING REMARKS

The airborne downlooking dye lidar demonstrated a capability to obtain quantitative information on quasi-instantaneous plume dimensions to over 100 km downwind during certain conditions, on plume rise, and on the height of the atmospheric mixing layer. The rates of chemical reactions, for instance, appear to be different on plume edges than in the central portions of plumes (Gillani and Wilson, 1980). Thus, information on the quasi-instantaneous dimensions and their relation to time-averaged dimensions would seem to be essential for the understanding and quantification of plume chemistry. The fact that the lidar plume dimensions compared more favorably with *in situ* counterparts, following empirical adjustments to ensure compatibility with respect to sampling time, stresses the need for such handling of diverse data sets. The use of such a procedure if proven to be appropriate for considerably longer sampling times, will enhance the ability of a tool such as airborne lidar for providing useful information for both chemical and meteorological applications, especially over wide areas.

Dispersion curves other than P–G exist such as those developed at Brookhaven (Singer and Smith, 1966) for elevated, non-buoyant plumes and by the TVA (Carpenter *et al.*, 1971) for specific power plants. However, these curves are site and/or source dependent (Gifford, 1976). Largely unverified rules-of-thumb for incorporating buoyancy and turning of the horizontal wind with height into existing schemes such as P–G have been suggested (e.g., Hanna *et al.*, 1977 and Irwin, 1979), and new schemes incorporating these effects have been proposed (e.g., Irwin, 1979). In both instances, these effects and those of turbulent diffusion have been assumed to be strictly additive; it is possible that significant interactions occur. Also, the latter are still in the developmental stage and currently require parameters not easily or routinely measured or estimated. Hence, at this point, no attempt was made to directly relate the lidar data to other such literature information.

When analysis of all the data collected during STATE 78 is completed, the information related to plume dispersion should be interrelated and then integrated. As such it will hopefully provide a data set useful in evaluating new or existing schemes for the estimation of plume spread from large, elevated buoyant plumes. Obviously, detailed information obtainable by airborne lidar as discussed in this paper are essential for such a purpose.

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